7.—SOME CAMBRIAN BASALTS FROM THE EAST KIMBERLEY, WESTERN AUSTRALIA.

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I. NOTES ON FIELD OCCURRENCE.

By E. de C. Clarke, University of Western Australia.

INTRODUCTION.

The Kimberley Land Division, which has an area of 144,000 square miles, occupies the northernmost part of Western Australia (Fig. 1). In it have been found representatives of nearly all the formations which occur in other parts of the State, and it has, in addition, rocks of Cambrian and Devonian age. In its south-west part is a rather unique suite of alkaline eruptives, and in its northern and eastern parts a considerable development of basalts.

The basalts of the eastern part, with which we are here concerned, extend into Northern Australia, and occur over a large area between latitudes 15° and 19°, and longitudes 128° and 130° (Fig. 2). Some of them, at least, are of Cambrian age, and are reported to attain a thickness of as much as 3,000 feet in some localities.

The Kimberley is more than 1,000 miles from the main centres of population in Western Australia. Until the recent development of air services, the quickest means of reaching it was by a sea voyage of about ten days. Population and means of land communication are still very meagre, and, although the first gold discoveries of any importance in Western Australia

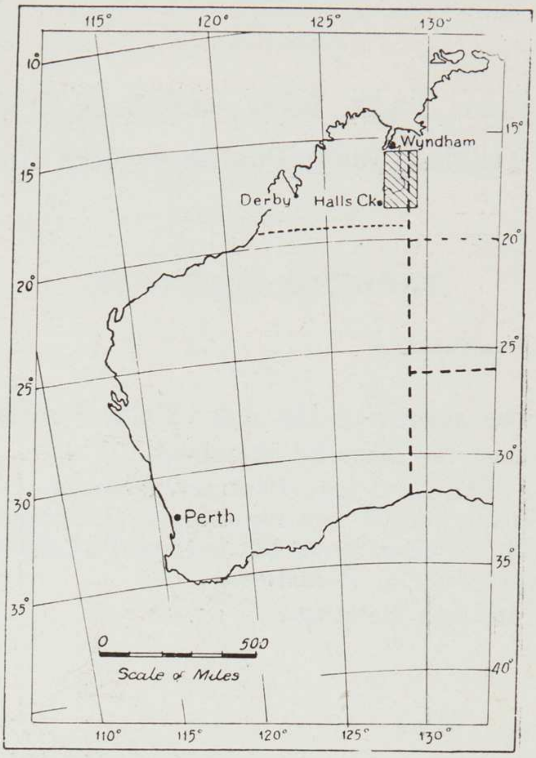

Fig. 1.—Locality Map showing the situation of the rocks under discussion (shaded area), and the position of Kimberley (north of the dotted line).

were made near Hall's Creek in about 1884, results were disappointing. There was no inducement, from the purely economic standpoint, for a systematic geological survey of the Division or of any part of it until, in about the year 1920, small amounts of mineral pitch and oil were found in Cambrian and in Permian rocks. These discoveries resulted in the detailed examination of a small area by Mahony (1922), to reconnaissances by Wade (1924) and Blatchford (1927), and finally to the extensive and detailed survey of a part of the West Kimberley by Wade (1936). From the time of the pioneer work of Hardman (1885), several geologists have also examined parts of the Division in order to determine its resources in gold or artesian water. They have thus had no reason to pay much attention to the basalt. All their reports, however, refer to the wide distribution of this rock, particularly in the eastern and northern parts of the Division.

During August and September, 1927, I was privileged to accompany the late Mr. T. Blatchford, Government Geologist of Western Australia, on a tour of inspection from Wyndham to Derby. The specimens described by Dr. Edwards were obtained during this journey, but I was not particularly interested in the basalt, and only made notes on it as a matter of course. I am much indebted to Mr. M. P. Durack for hospitality and guidance during the earlier parts of the trip, and to the Freney Kimberley Oil Co. and Mr. H. W. B. Talbot for a similar courtesy during its later part, also to Dr. Arthur Wade who read this part of the paper in MS. and made some valuable suggestions.

Although the conditions of travel under which the collection was made did not permit of a proper investigation of field occurrence, it is desirable that such an important petrological contribution as this should be prefaced by some attempt to describe the "geological setting."

Nearly all the specimens examined by Dr. Edwards were obtained in the Antrim natural region (Clarke, 1926) or Ordland (Jutson, 1934), which is topographically different from the adjoining North Kimberley natural region because of geological differences. The Antrim Region is made up

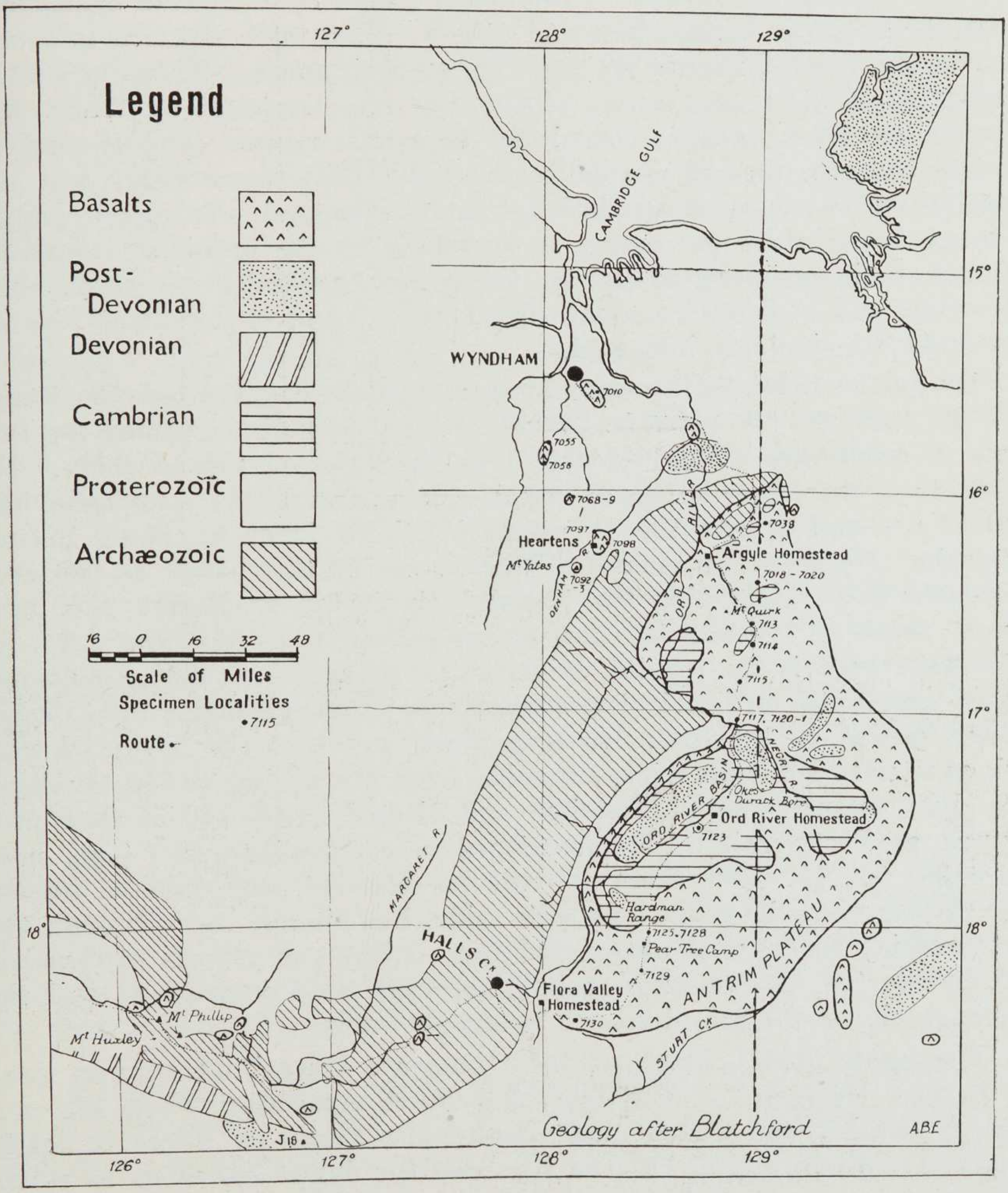

Fig. 2.—Geological Sketch Map of part of East Kimberley and the adjoining part of Northern Australia, showing the distribution of the basalts and the localities of the specimens described in the text.

mainly of basalts and Cambrian sediments which are in most places nearly horizontal; the North Kimberley has an eastern fringe of closely folded metamorphic Archaeozoic rocks overlain by more gently folded Proterozoic rocks, which are at most only slightly metamorphosed.

The sketch map (Fig. 2), which is almost altogether a copy of Blatchford's (1927) compilation from his own observations and those of previous observers, shows that in the East Kimberley "basalt" occurs:—

(a) in small patches associated with Pre-Cambrian rocks,

(b) in large areas associated with Cambrian rocks.

PUBLISHED OPINIONS REGARDING THE AGE OF THE BASALTS.

It is necessary in the first place to realise that views as to the age of the different formations in the Kimberley have changed, and particularly that the rocks marked "Proterozoic" on Figure 2 were considered to be Devonian by Logan Jack and others. This interpretation is found even in the title of Figure 48, page 29, of Maitland's "Summary of the Geology of Western Australia" (1919), but was disproved by Wade. Another cause of confusion in consulting the earlier reports is that, prior to Wade's surveys, the distinction between the Proterozoic rocks and the fossiliferous Cambrian strata had not been recognised. To avoid complication I have, where necessary, in summarising the opinions of others, changed their age-designations to those now generally accepted; such alterations are enclosed in square brackets [ ] and any explanations or comments are similarly indicated.

Hardman (1885) in his second report (on the country between longs. 126° 30′ and 129° 30′ and lats. 16° 40′ and 19° 00′) distinguished the two types of occurrence ("field groups") (a) and (b) mentioned above. He stated that the larger areas of basalt (field group (b)) underlie the [Cambrian] and overlie the [Proterozoic], both junctions being unconformable. He gave two measured thicknesses of this basalt as 900 feet and 1,100 feet. Regarding the [basalt] (indicated on Figure 2 of this paper) south of latitude 18° and between longitudes 126° and 127°, he said that there is no precise evidence as to age, but strong evidence [based apparently on lithological resemblance] that it belongs to the same igneous period as the extensive lava flows, and that the "belt of trap rock quarter to half-mile wide, traceable from Mt. Phillip to Mt. Huxley" is a dyke intrusive into quartzites and altered grits [which are now mapped as Proterozoic]. He mentioned other, similar cases (e.g., near J18 (126° 50′, 18° 55′) where a lenticular mass of amygdaloidal basalt, four or five miles long and one mile wide, has "burst up" through the [Proterozoic] rocks) and also noted that dykes and masses of basaltic rock invade the [Archaeozoic rocks], but that these instrusions and the [Archaeozoic] rocks are alike cut by quartz veins.

Woodward (1891) wrote of the "immense tracts" of country near the Border [between the Kimberley and North Australia] which are covered by basalts, and stated that basalts also occur as dykes in many places. [It would appear that he regarded the dykes and flows as essentially contemporaneous] but he did not express any opinion as to their geological age.

Jack (1906) dealt only with the basalt belonging to field group (b). He thought it likely that the basalt near Argyle Homestead is Kainozoic —much younger than the Antrim Plateau basalt. The Argyle basalt has, he wrote, "all the appearance of having simply levelled up a depression formed by the converging Bow and Ord Rivers." Between Rosewood Homestead and Mt. Quirk is a basalt puy, near which the lavas much exceed in thickness the 300 feet which is the average for the Argyle basalts. On the other hand, the Antrim Plateau basalt is at least 660 feet thick.

Mahony (1922) described the structure of the Ord River Basin [a descriptive term later introduced by Wade (1924)]. The basalt in this basin is comformably overlain by Cambrian limestone, but its relation to the underlying [Proterozoic] hard grits and conglomerates, which also dip east, is not stated. [He estimated the basalt to be 4,000 feet thick—much more than any other observer made it.]

Wade (1924) described the Ord River Basin as being "completely surrounded and underlain by basalt," that in places encloses large masses of quartzite which stand out above the basalt plains. There is no discordance in dip between the basalt and the Cambrian sediments above it or the [Proterozoic] below. The Okes-Durack bore penetrated 408 feet of basalt, and did not reach the base of the formation. [From the particulars regarding "ashy" and vesicular layers, the 408 feet is made up of six flows.] Two periods of earth movement are recorded in the Ord River Basin—one post-Cambrian and one post-Permian. The latter was responsible for a good deal of thrust faulting. [Farquharson (1923) also concluded, from a petrological study of the basalt from near the junction of the Ord and Negri Rivers, that there is a shear zone in the basalt. If such movements occurred they may have obscured the relations of the limestone and basalt and caused Jack to think that the basalts in group (b) belong to two ages.] Wade saw no evidence for the puy [described by Jack]. The basalts south of Argyle Homestead gradually sink under the plain and the limestone appears again in solid beds [which seems to imply that the Argyle basalt underlies the Cambrian limestone as does the basalt in the Ord River Basin]. There is an extensive development of basalt 26 miles north of Argyle Homestead which has been involved in earth movements. He also stated that "14 miles south of Wyndham on the estuarine plain of the Ord," basalt forms "little rises all over the plain," and there occur "what appear to be basaltic cones." [It is not clear whether the basalt near Wyndham (spec. 7010, group 4)*, described as a dyke by Woodward (1891) and Maitland (1902) is part of this occurrence.] On Hicks Creek, north of Argyle Homestead, the basalt is "full of veins of quartz." [Quartz veins in basalt were seen by me only at Mt. Yates (Blatchford (1928)), and the feature does not seem to be recorded elsewhere for field group (b).]

Blatchford's (1927) report, though published later than Wade's, puts forward the results of field work in which these two geologists collaborated, and shows no material divergence from Wade's views as to the basalt.

Blatchford (1928) described the geological features noted in part of the journey which was mentioned at the beginning of this paper. Where the route traversed the North Kimberley natural region he considered that there was one suite of lavas and tuffs contemporaneous with the [Proterozoic] sediments and another of later date. The basalt near Argyle Homestead probably underlies the Cambrian limestones. No comparison of the ages of

* Referring to the number of the specimen in the collection of the Department of Geology, University of Western Australia, and to the group to which Dr. Edwards has assigned it.

the Argyle basalts with those in the North Kimberley natural region is made. Petrological notes by Dr. C. O. G. Larcombe are included in this report.

Summary.—Basalt in the East Kimberley has been described or mentioned by all geologists who have reported on the region; Jack and Wade alone express definite opinions as to the contemporaneity or otherwise of the occurrences which they saw, and those opinions are opposed.

FIELD OCCURRENCE OF MATERIAL EXAMINED.

Basic intrusions in Proterozoic rocks.—Regarding these, which comprise nearly all of field group (a), my field observations were confined to a small area in the North Kimberley, and are contained in Blatchford's report (1928). Of my specimens, the only ones fit for detailed examination are from intrusions in supposed Nullagine (Proterozoic) rocks. The specimens are 7068 and 7069 (group 7) and 7056 (group 1). It is particularly unfortunate that specimens 7092 and 7093, from Mt. Yates, which is a plug invading Proterozoic rocks (Blatchford, 1928, p. 13 and fig. 10), are too weathered to be any use.

Cambrian basalt outcropping in the Negri River.—In the Negri River, about 1½ miles above its junction with the Ord is the section mentioned by Blatchford (1927, p. 42 and fig. 37). The low cliff is composed from above downwards of about 30 feet of the "basal" Cambrian limestone (Blatchford, 1927 p. 15 and description of fig. 37); below this is about five feet of sandstone, which in places wedges out; the next bed (probably either a volcanic breccia or a flow) is much decomposed and passes down into a massive basalt (specs. 7117, 7120, and 7121 (group 3)), with very numerous amygdales most of which are siliceous. Impsonite occurs in vesicles and cracks in the more "solid" lower part of the basalt (Farquharson, 1923, p. 11).

Specimens were taken from two other localities in which basalt, apparently in the same stratigraphic position as the basalt in the Negri River, is exposed:—

(a) In a creek which is crossed by the Wyndham-Hall's Creek track ten miles south of Hardman Range. Here solid basalt (spec. 7125, group 4) is overlain by bedded rocks—apparently tuffs—above which is limestone about 30 feet thick, lithologically resembling the limestone which occurs at the east end of Hardman Range and which contains the Cambrian fossil *Biconulites hardmani* (Spath, 1936) formerly known as *Salterella.*

(b) At Pear Tree Camp flow-basalt (probably spec. 7128, but the label was lost in transit from the field) is overlain by agglomerate and by well-bedded tuff containing calcareous bands. The uppermost rock seen is a limestone, lithologically like the "Salterella" limsetone. If the limestone represents approximately the same stratigraphical horizon as that of the limestone in the Negri River near its junction with the Ord, and if the basalt is, as mapped by Blatchford and Wade, continuous with that in the Negri, then limestone and basalt should be conformable near Pear Tree Camp, but the impression is that the limestone overlies the basalt uncomformably.

Basalt forming much of Antrim Plateau and of Plains near Argyle Homestead.—Hearten's Homestead (long. 128°15′, lat. 16°18′) is in the North Kimberley natural region, with Pre-Cambrian rocks to the east and west. Round it is a small plain underlain by basalt (specs. 7097 and 7098, group 2). The occurrence is mentioned here, because, although 35 miles east of Argyle Homestead it may be a survival of a once wider extension of the Argyle basalts next to be described.

Figure 3 gives one possible interpretation of the geology within a few miles of Argyle Homestead*, from which it is evident that, in my opinion, the Argyle basalts are younger than the Cambrian limestones and other sediments, and overlie them unconformably. However, this is only an opinion.

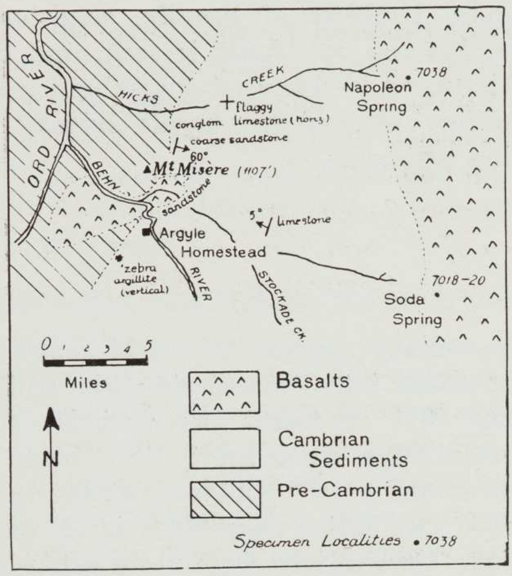

Fig. 3.—Geological Sketch Map of the country near Argyle Homestead, East Kimberley.

Careful geological mapping of the area is necessary, and such a survey would not be easy because outcrops are poor, and relief and dips are both low, except near Mt. Misère. Farther south in this area of "Argyle basalt" there are several cuesta-like hills surrounding and including Mt. Quirk. They are, judging from information from Mr. M. P. Durack and from the geological maps of Wade and others, composed of basalt, which, the topography suggests, may be in the form of a number of flows dipping gently away from the neighbourhood of Mt. Quirk. These basalt flows are at a distinctly higher level than the limestone "walls" described by Wade as having basalt both to the east and to the west. It appeared to me that the limestone of these "walls" is dipping in different directions at low angles; if this is so, the "walls" might be interpreted as the highest part of a land surface, the rest of which has been covered by basalt flows. No definite fossils have been reported from the limestones of this locality, but Wade considered them to be Cambrian, and lithologically they resemble the "Salterella" limestones to the south and to the north. Again, about five miles north of the Negri River it was noticeable that for two or three miles to the east of the Wyndham-Hall's Creek track are flat-topped hills, seemingly composed of horizontal flows of basalt, east of which is a large expanse of limestone country which is clearly at a lower level than the basalt.

*Specimens 7018-7020 and 7115, group 1, 7038 and 7113, group 3, 7114, group 4, were obtained either from this area or from its southern extension. (See Fig. 2.)

Six or seven miles south of Pear Tree Camp, where, as already stated, basalt which seems best assigned to the Negri group occurs, the track rises onto the Antrim Plateau; the difference in level between Pear Tree Camp and the Plateau is about 350 feet by aneroid readings. The basalt (spec. 7129, group 6) which outcrops on the Plateau appears much less weathered than that at Pear Tree Camp, and, judging by the topography, should overlie the Cambrian limestone, not underlie it as does the basalt in the Negri River.

The basalt on the Antrim Plateau seems to be but a thin layer, for, in a gully on the edge of the Plateau, about seven miles S.E. of Flora Valley Homestead, 15 feet of spheroidally weathered basalt (spec. 7130, group 3) overlies conglomerate containing boulders of granite, sandstone, and quartz. In several places on the Plateau, no basalt is seen, and the ground is strewn with water-worn pebbles and boulders of quartz and granite. This seems to indicate that erosion has removed the basalt entirely in some places and exposed the underlying sediments.

CONCLUSIONS AS TO AGE RELATIONS.

Hurried field observations suggest that field group (a) consists mainly, if not entirely, of intrusions into Proterozoic rocks and that the large areas of basalt (field group (b)) represent two periods of vulcanism, one (of which the outcrops in the Negri River are typical) being Cambrian, the other (which gave the basalt found on the Antrim Plateau and near Argyle Homestead) being younger. This latter suggestion is at variance with the conclusions of others whose observations were more extensive than mine: Jack thought the Antrim and Argyle basalts to be of different ages, Wade and others inclined to the view that all the basalts of field group (b) are contemporaneous. Dr. Edwards informs me that, from the petrologist's point of view, there is no suggestion that basalts of two ages are represented—rather the reverse.

The following tabular comparison of field and petrological classification shows that, at any rate until much more field work has been done, the suggestion that the East Kimberley basalts are anything but a single series may be disregarded.

—		Field Classification.		
		Field Group (*a*).	Field Group (*b*).	
			Cambrian.	Post-Cambrian.
Petrological Classification	Group 1 ...	7056	...	7018–20, 7115
	Group 2 ...	7092, 7093	7128	7097, 7098
	Group 3 ...	...	7117, 7120, 7121	7038, 7113, 7130
	Group 4 ...	7010	7125	7114
	Group 6* ...	...	...	7129
	Group 7 ...	7069	...	...

* Group 5 is not represented in specimens from the Kimberley examined up to date.

II. PETROLOGY.

By A. B. Edwards, University of Melbourne.

INTRODUCTION.

The following notes are intended to supplement our meagre knowledge of the petrology of the East Kimberley basalts. They are based on the examination of a small collection of East Kimberley basalts, which was made during a reconnaissance trip by Professor E. de C. Clarke, who kindly placed the specimens at my disposal. The localities from which the specimens come are shown in the accompanying sketch map (Fig. 2). The examination was carried out in the Geology Department of the University of Melbourne by the kind permission of Professor Skeats. Of the six new chemical analyses submitted, five were made by the author, and the sixth by Mr. R. W. Fletcher in the Government Chemical Laboratory at Perth, under the direction of Dr. E. S. Simpson, by whose permission it is reproduced here. In addition, two specimens from the North-West Land Division and from North Australia respectively, which seem to belong to the same assemblage, are described.

PETROLOGY.

Several of the specimens in the collection (Nos. 7092, 7093, 7123, and 7128*) have been extensively altered, and the original material of the rock is largely replaced by limonite, and quartz in veins and stringers. Only the general appearance of a basaltic texture is preserved in these specimens, and in (7092, 7093) the outlines of plagioclase phenocrysts about 1 mm. long can be made out. It is unfortunate that these particular specimens should be so altered, since they are from a plug clearly intrusive into Nullagine quartzites at Mount Yates, on the Denham River (lat. 16° 20′, long. 128° 05′), the most definite evidence of intrusion that Professor Clarke saw during his journey.

The remainder, however, are sufficiently fresh for their mineral composition to be determined in some degree. All but one specimen (7192) are extremely fine-grained, and there is a general similarity about them. Despite this it has proved possible to classify them into several distinct, though perhaps gradational, groups. Chemical analyses have been made of the most typical rock in each group.

1. *Olivine-basalts.*

(7056) about 6 miles south of Fish Pool (lat. 15° 50′, long. 128°), underlain by red shale.

(7018) about 1 mile east of "Soda Spring" (east of the Argyle Homestead). This rock comprises the bulk of the hills about here.

(7019) same locality as (7018).

(7020) same locality as (7018).

(7115) about 40 miles south of the Argyle Homestead, on the track to Hall's Creek (lat. 16° 45′, long. 128° 58′).

These are extremely fine-grained aphanitic basalts, consisting of numerous small microphenocrysts of olivine (0.3 mm. across) and clots of equally small felspar crystals, set in a ground mass of plagioclase laths, augite and iron ore. The olivine is nearly always completely altered to serpentine, with

* Numbers thus (7128) refer to specimens in the rock collection of the Geology Department of the University of Western Australia.

a rim of iron oxide, while the felspar phenocrysts are saussuritized. The groundmass plagioclase has a maximum extinction angle of 25° in the symmetrical zone, corresponding to a composition Ab_{55}. The pyroxene, which is the least altered mineral, is colourless to greenish-brown, biaxial, positive, and has an optic axial angle (2V) greater than 45°, so that it is probably diopsidic. The iron ores form small shreds and needles scattered sparsely through the rock, and sometimes enclosed in augite grains. In (7020) patches of greenish chlorite are developed, while in (7018) and (7019) the groundmass consists of plagioclase laths in a glassy base. The glass, which was iron-rich, is now reddish-brown through the alteration of the iron oxide trichytes and dust to limonite.

A chemical analysis of (7056) is given in Table I, No. 1, and shows that these rocks resemble in chemical composition certain of the Tertiary Newer Volcanic olivine-basalts of Victoria (Table I, A). Like them it is relatively rich in SiO_2, being only slightly under-saturated with respect to silica.

TABLE I.

Analysis.	1.	A.
SiO_2	50·00	49·86
Al_2O_3	15·13	14·35
Fe_2O_3	3·06	4·21
FeO	6·07	7·02
MgO	8·33	8·25
CaO	9·10	8·45
Na_2O	2·59	2·80
K_2O	1·81	1·23
H_2O+	0·91	...
H_2O-	0·50	...
CO_2	0·20	0·04
TiO_2	1·25	1·62
P_2O_5	0·55	0·38
MnO	0·17	0·18
	99·67	

Norms.	1.	A.
Q	...	1·81
Or	10·69	7·13
Ab	21·92	23·18
An	24·32	26·95
Ne	...	0·30
di	13·97	12·69
hy	15·52	13·72
ol	3·83	5·88
mg	4·42	5·17
hm	...	0·22
il	2·38	3·08
ap	0·66	0·45
cal	0·46	0·08

1. Olivine-basalt (7056), about 6 miles south of Fish Pool (lat. 15°50′, long. 128°), East Kimberley. *Analyst*—A. B. Edwards.

A. Average Footscray basalt (16 analyses), Victoria. (A. B. Edwards, *Quart. Journ. Geol. Soc. Lond.*, **xciv.**, p. 809, 1938. Note.—Norms averaged and not recalculated, in order to show how these rocks border between over- and under-saturation).

2. *Felspar-basalts.*

(7097), 2 miles north-west of Hearten's Homestead (lat. 16°16′, long 128°15′). This basalt makes up the bulk of the low country near the creek on which the homestead stands.

(7097, a), same locality.

(7098), 2 miles east of Hearten's Homestead, probably underlying the sandstones and conglomerates of "Conglomerate Range."

The distinctive feature of these three specimens is the presence in them of clots of plagioclase crystals, the clots being as large as 1 cm. in diameter. They are composed of prismatic crystals about 1 to 2 mm. long, which show zoning and lamellar twinning, with a maximum extinction angle of 30° in the symmetrical zone, so that their composition is about Ab_{45}. The extinction angle is frequently masked by the alteration of the felspar to saussurite, sometimes accompanied by epidote.

The clots are set in a fine-grained intergranular groundmass of felspar, pyroxene, iron ore, and a little devitrified green glass. The groundmass felspar is generally lath-shaped, and is somewhat saussuritized plagioclase of composition about $Ab_{45\text{-}50}$. The pyroxene is colourless when fresh, but is often altered to a fibrous greenish chlorite. It is usually granular, but the grains are too small for their optical character to be determined. They show extinction angles as high as 40°, so that they are probably relatively lime-rich. The iron ores are coarse-grained, with a tendency to square cross-sections, indicating magnetite. They approach the size of microphenocrysts, compared to the individuals of the groundmass.

(7097,a) appears to be a chilled phase of (7097). The felspar phenocrysts in it occur as individuals rather than as clots, and the groundmass is much more glassy. The iron ores occur as trichytes throughout the glass, and have been partially altered to limonite, so that the rock appears brown even in thin section. Secondary silicification has accompanied the limonitization, quartz appearing as stringers across the section. There is some resemblance between this specimen and the specimens from Mt. Yates (7092, 7093). (7128), probably from near Pear Tree Camp, 11 miles south of the Hardman Range might also be of this type.

A chemical analysis of (7098), (Table II. No. 1), reflects the general characters of the rock in its high lime and alumina contents. The low MgO corresponds with the absence of olivine. The analysis resembles in many respects that of a porphyritic felspar basalt from the Tertiary Newer Volcanic series of Victoria, occurring at Rocky Range, Lancefield (Table II, A).

TABLE II.

	Analyses. 1.	Analyses. A.		Norms. 1.	Norms. A.
SiO_2	51·80	48·49	Q	2·58	...
Al_2O_3	18·14	18·65			
Fe_2O_3	2·45	4·77	Or	11·19	10·51
FeO	6·61	7·07	Ab	23·01	29·52
MgO	3·98	4·65	An	31·71	29·98
CaO	8·50	8·27			
Na_2O	2·72	3·49	di	7·26	5·83
K_2O	1·89	1·79	hy	15·36	3·94
H_2O+	1·04	0·28	ol	...	8·60
H_2O-	1·05	0·60			
CO_2	0·05	*nil*	mg	3·53	6·93
TiO_2	0·75	1·37	il	1·43	3·85
P_2O_5	0·41	0·60	ap	1·00	1·42
MnO	0·08	0·15	cal	0·11	...
BaO	...	0·01			
	99·47	100·19			

1. Felspar-basalt (7098), 2 miles east of Hearten's Homestead (lat. 16°16′, long. 128°15′), East Kimberley.

A. Porphyritic-andesine-basalt, E. slope of N. point of eruption, Rocky Range, Parish of Lancefield, Victoria. (A. B. Edwards, *Quart. Journ. Geol. Soc. Lond.*, **xciv.**, 1938, Table V., No. 12. Note.—Fe_2O_3, 2.77, should read 4.77).

The Victorian rock is distinctly under-saturated in SiO_2, however, while (7098) shows a slight excess of SiO_2. The Victorian rock is also richer in MgO and in Na_2O, which resides mainly in the groundmass felspar and glass, since a partial analysis of the felspar phenocrysts shows them to have a composition about Or_5 Ab_{44} An_{51}. The other type of rock which (7098) resembles in some respects is the Bunbury tholeiite, but this is distinctly poorer in alumina and rather richer in lime (Edwards, 1938).

3. *Aphyric basalts* (*Argyle Type*).

(7120), Negri River, about 1 mile above its junction with the Ord River, and from near the upper surface of the basalt, *i.e.* close to its contact with the adjacent Cambrian limestone.

(7117), same locality as (7120).

(7121), same locality as (7120).

(7113), Behn Creek, about 23 miles south of the Argyle Homestead, on the track to Hall's Creek (lat. 16°32′, long. 128°58′).

(7038), Napoleon Spring, 13 miles north-east of the Argyle Homestead.

(7130), about 8 miles east-south-east of Flora Valley Homestead, on the track to Hall's Creek. Basalt from the western edge of the Antrim Plateau.

This variety of basalt appears to be prominent in the vicinity of Argyle Downs, while its occurrence on the western edge of the Antrim Plateau suggests that it may be widespread. At the Negri River locality (7120) it definitely underlies Cambrian limestone. Despite its distinctive appearance in thin section, it is difficult to give it a suitable descriptive name on account of its fine-grained aphyric texture. It is suggested, therefore, that it may be distinguished by a local name as the *Argyle Type*.

The analysed specimen (7120), from the Negri River locality, is a fine-grained rock composed of stumpy laths of plagioclase (0.2 mm. x 0.05 mm.) which sometimes occur in clusters, together with smaller granules and prisms of colourless pyroxene, which is sometimes greenish from partial alteration to chlorite, coarse, irregularly rectangular areas of magnetite (0.2 mm. x 0.2 mm.) fringed with iron stains, and intersertal areas of light brown glass and apple-green material of chloritic appearance. The amount of felspar about equals the amount of pyroxene and glass. The laths show a maximum extinction angle in the symmetrical zone of about 30°, corresponding to a composition of Ab_{45}. In view of the relatively low CaO content and high Na_2O content of the analysis (Table III., No. 1), the brown glass must be largely felspathic, with a high soda content. The pyroxene has a low double refraction, and an extinction angle of about 40° on prism faces. It appears to be biaxial, positive, with 2V greater than 45°, but most grains are too small for determination. Small circular areas of fibrous zeolite, of low double refraction, occur occasionally within patches of the green glass.

(7117) is identical with (7120), except that the plagioclase is partially saussuritized, and (7038) differs only in the presence of infrequent microphenocrysts of altered plagioclase 1 to 2 mm. in length. The groundmass plagioclase has a composition about Ab_{50}, and one or two pyroxene grains showed acute bisectrix figures with 2V greater than 45°, indicating that it is lime-rich or augitic. (7113) from Behn Creek is generally similar, but the pyroxene is completely unaltered, and the amount of glass is very small. The plagioclase appears to be slightly more basic than in (7120).

(7130) from the western edge of the Antrim Plateau, differs from (7120) in that the iron ore is present in smaller but more numerous crystals, mostly in the brown glass. Considerable calcite occurs in small patches throughout the specimen, and the areas of green glass are associated with a little interstitial quartz (apparently primary), which is accompanied by occasional small crystals of hornblende, pleochroic from straw yellow to greenish brown. This rock appears to be intermediate between the Argyle basalts, as represented by (7120), and the typical quartz-basalts described below.

4. *Quartz-basalts.*

(7125), from 9 miles south of the Hardman Range, on the track to Hall's Creek, near J. 32.

(7114), from "Sugar Spring," on the track from the Argyle Homestead to Hall's Creek (lat. 16°37′, long. 128°58′). This basalt is the general rock about here.

(7010), from "The Seven Mile," near Wyndham, on the road to the Argyle and Ord River Stations.

(7125), which is the analysed specimen (Table III., No. 2), contains numerous microphenocrysts of pyroxene, frequently with prismatic outlines, and about 0.3 mm. long. They are colourless to greenish grey and frequently cluster around relatively coarse, squarish grains of iron ore (0.3 mm. diameter). The pyroxenes in these clusters are stained with iron oxide along cleavages and cracks. The more idiomorphic crystals occur separate from the iron ore grains. Two types of pyroxene appear to be present. A number of crystals are biaxial, positive and have 2V larger than 45°, and an extinction angle of 35°-40°, so that they are lime-rich augites. Occasional crystals, however, appear to be almost uniaxial, so that some proportion of pigeonite accompanies the augite.

TABLE III.

	1.	2.	3.	4.	5.
SiO_2	53·95	54·40	52·58	52·67	50·50
Al_2O_3	15·98	14·34	10·56	14·34	14·25
Fe_2O_3	2·99	8·60	7·10	2·37	0·58
FeO	8·49	5·32	9·12	6·95	11·36
MgO	3·95	3·44	3·62	7·32	5·01
CaO	5·35	7·25	5·94	6·99	10·15
Na_2O	3·10	2·27	3·53	3·20	2·58
K_2O	2·00	1·95	2·80	1·92	1·39
H_2O + ...	1·25	0·34	1·33	1·99	0·35
H_2O —	0·65	0·56	0·56	0·38	0·62
CO_2	tr.	0·20	*Nil*	0·06	1·83
TiO_2	1·00	1·25	2·62	1·02	1·22
P_2O_5	0·68	0·30	n.d.	0·09	0·05
MnO	0·17	0·21	0·42	0·39	0·28
FeS_2	...	...	*Nil*	0·09	...
	99·56	100·43	100·18	99·78	100·13

Norms.

	1.	2.	3.	4.	5.
Q	6·65	15·70	5·39	...	0·73
Or	11·80	11·52	16·55	11·35	8·24
Ab	26·22	19·19	29·88	27·05	21·81
An	23·80	25·98	4·73	19·15	23·70
di	0·39	4·89	19·84	11·60	12·20
hy	21·43	7·23	6·59	22·43	25·26
ol	...	...	...	...	...
mg	4·40	12·47	10·30	3·34	0·87
il	2·83	2·41	4·98	1·94	2·33
ap	0·80	0·34	...	0·03	0·06
cal	...	0·46	...	0·14	4·16

1. Argyle basalt (7120), Negri River, about 1 mile above its junction with the Ord River, East Kimberley. *Analyst*—A. B. Edwards.
2. Quartz-basalt (7125), 9 miles south of the Hardman Range, on the track to Hall's Creek. *Analyst*—A. B. Edwards.
3. Basalt (cf. 7010), from well at the 6-mile, south-east of Wyndham, Kimberley District. *Analyst*—C. G. Gibson. (*Bull. G.S.W.A.*, 67, p. 22, No. 3779.)
4. Sub-ophitic basalt (7129), Flora Valley Station, about seven miles south of Pear Tree Camp, and 18 miles south of the Hardman Range, on the track to Hall's Creek. *Analyst*—R. W. Fletcher.
5. Aphanitic basalt (7069), hills west of flat at Martin's silver-lead mine (lat. 16°21′, long. 128°)—part of a large intrusion. *Analyst*—A. B. Edwards.

These small microphenocrysts of pyroxene and iron ore are set in a groundmass of plagioclase laths, granular to prismatic pyroxene, a little intersertal felspathic glass with a brownish tinge, a minor quantity of iron ore of late crystallization, and interstitial patches of relatively coarse-grained quartz. The quartz is usually accompanied by small sub-idiomorphic prisms of hornblende, which is pleochroic from straw yellow to greenish brown, and has an extinction angle of about 20° on the prismatic cleavage. The hornblende prisms occur between quartz grains and around the margins of the quartz areas. They are sometimes moulded on the coarser iron ore crystals, and on the pyroxene microphenocrysts, and occasionally appear to be intergrown with laths of plagioclase. There seems little doubt that the quartz and hornblende are primary minerals, representing the final residuum of the lava from which these rocks were derived. The groundmass pyroxene is colourless when fresh, but is largely altered to a fibrous green chloritic material. The grains are too small for their optical properties to be determined, but may be assumed to be pigeonite, in view of the composition of the microphenocrysts. The felspar is plagioclase of a composition about Ab_{45}. The groundmass iron ore is in small grains and rods, and is sometimes moulded on the pyroxene.

(7114), from "Sugar Spring," carries occasional phenocrysts of partially saussuritized plagioclase which shows zoning. The cores of these crystals show extinction angles of about 30° in sections parallel to (010), while the rims extinguish at 15°. These values correspond to compositions of Ab_{30} for the core and Ab_{50} for the margin. The groundmass felspar has about the same composition as the margins of the microphenocrysts. The pyroxene phenocrysts appear to be lime-rich augites, in that a few crystals gave positive acute bisectrix figures with 2V greater than 45°. The iron oxides are coarsely rectangular and sparsely distributed, and a few prisms of hornblende accompany the small areas of interstitial quartz.

In (7010), from "The Seven Mile," near Wyndham, the pyroxene microphenocrysts are fewer but larger (1 mm. long) and sub-idiomorphic. They show positive acute bisectrix figures with 2V greater than 45°. The early formed iron ore crystals are not as large as those in (7125), and the pyroxene microphenocrysts, about 1 mm. long, are also present. They are relatively unaltered, with coarse lamellar twinning, and appear to be labradorite (Ab_{45}). Hornblende prisms accompany the areas of interstitial quartz, as in (7125), and here and there there are serpentine pseudomorphs, apparently after microphenocrysts of olivine. It seemed possible that this specimen might correspond to an analysed specimen (G.S.W.A. 3779) from a well six miles south-east of Wyndham (Table III, No. 3), but the analysis is scarcely comparable with that of (7125) (Table III, No. 2). The high Fe_2O_3 in both suggests that they have both undergone partial replacement by limonite, though it may be partly a reflection of the numerous coarse crystals of magnetite. The very low Al_2O_3 of (G.S.W.A. 3779) is perhaps attributable to leaching out of alumina during this process. Even so, there is no agreement as to soda, potash and lime content, and the amounts of these oxides present are scarcely reconcilable with the compositions of the felspars in (7010). The analysis of (G.S.W.A. 3779) compares much more closely in these respects with that of the Argyle basalt (Table III, No. 1).

5. *Pyroxene-basalt.*

(7174), Kelly's Yards, Victoria River, Northern Territory, at the junction of the Dry River, Victoria and Western Australian stock routes. The rock is intrusive into limestone, but is also overlain by sandstone and limestone. (Collected by H. A. Ellis.)

This rock is composed of abundant phenocrysts of pyroxene with occasional large laths of altered plagioclase, in a much altered intersertal groundmass of altered pyroxene, saussuritized laths of plagioclase, iron ore, and abundant devitrified green glass. The pyroxene phenocrysts are squarish to rectangular crystals, about 1 mm. to 1.5 mm. across, and often slightly corroded. Sometimes they occur in clots. They are colourless, biaxial, positive, with 2V greater than 45°, and a moderate birefringence, so that they are presumably augite. They are generally fringed with fibrous greenish-brown alteration product, and occasionally enclose small crystals of iron-stained serpentine, pseudomorphous after olivine. Similar pseudomorphs occur in the groundmass. They resemble in size and appearance the olivine crystals in the olivine-basalts described above. The felspar phenocrysts were originally plagioclase in the form of laths about 2 mm. x 0.5 mm., but are too altered to saussurite for their original composition to be determined. Coarse, more or less square crystals of iron ore (0.2 mm. across) are also prominent against the altered groundmass.

6.—*Sub-ophitic basalt.*

(7129), Flora Valley Station, about seven miles south of Pear Tree Camp, and 18 miles south of the Hardman Range, on the track to Hall's Creek (lat. 18°07′, long. 128°25′).

The collection contains only one example of this variety of basalt, which is a relatively coarse-grained, sub-ophitic basalt consisting of laths of plagioclase and prisms of pyroxene in a base of interstitial plagioclase and minor amounts of iron ore. By comparison with the other basalts of the collection it is decidedly coarse-grained. The plagioclase laths mostly give extinction angles of about 25°, corresponding to a composition Ab_{55}, but one or two have angles as high as 35° corresponding to Ab_{35}. The high Na_2O content of the analysis (Table III., No. 4) suggests that the interstitial felspar of the base, which occurs as plates, some with multiple twinning or untwinned, must be more sodic than these laths. The pyroxene prisms are frequently partially altered to a fibrous yellow-green chlorite. When fresh they have a colourless core and a brownish to violet rim. They are biaxial and show a positive acute bisectrix figure, with 2V greater than 45°, so that they are probably augites. Their sub-ophitic intergrowth with the plagioclase laths sometimes produces a maltese-cross arrangement of the crystals. Occasional patches of bright green serpentinous material appear to be pseudomorphous after corroded olivine crystals.

7.—*Aphanitic basalt.*

(7069), from the hills west of the flat at Martin's Silver-lead mine (lat. 16° 21′, long. 128°). Part of a large intrusion.

This specimen is an extremely fine-grained rock of basaltic appearance, but it so much altered that little can be made out concerning its texture, except that it originally consisted of microlites or very small laths of plagioclase, minute granules of pyroxene, and particles of iron ore, possibly with some glassy base. An analysis (Table III., No. 5) confirms that it is of basaltic composition, on the border-line between saturation and undersaturation with respect to SiO_2, and in many respects comparable with the olivine-basalts described above. The high CO_2 content indicates the extensive alteration it has undergone. The analysis can be matched in some degree with analyses of some of the iddingsite-basalts of the Tertiary Newer Volcanic Series of Victoria (Edwards, 1938, b, Table V., Nos. 3, 4; Table VI., No. 2), but there are small discrepancies. From the notes by Professor Clarke which accompanied the specimens it seems probable that (7069) is the chilled margin of a gabbroic intrusion, represented by (7068), from the same locality. (7068) is a medium-grained gabbro consisting of allotriomorphic plates and laths of labradorite (Ab_{45}), grey to faintly violet pyroxene (2V greater than 45°), and abundant coarse iron ore grains (probably an intergrowth of ilmenite and magnetite). The iron ore appears to be the last mineral to crystallise, and is sometimes accompanied by small flakes of biotite. The pyroxene is somewhat chloritized.

A specimen (1785), from the Nullagine Series, two miles south-west of Nullagine, is closely comparable in appearance with this aphanitic basalt.

DISCUSSION.

The collection is too small to cover the whole range of basalt types and their differentiation products in the East Kimberley district, but the wide scatter of the localities from which the specimens were gathered make it probable that they are representative of some at least of the more common varieties. On this assumption it is possible to deduce the general petrological characteristics of this Cambrian basaltic area. The general resemblances between the types of basalt described above and their chemical similarities suggest that the East Kimberley basalts, as a whole, form a homogeneous petrographic province. No specimen in the collection is of a discordant type.

An outstanding feature of the collection is the relative scarcity of olivine in these rocks. Even in the olivine-basalt group, olivine is not the dominant mineral that it is, for example, in most of the Tertiary basalts of Victoria; and in the other East Kimberley rocks it is either rare or absent. This is in conformity with their chemical compositions. The analyses indicate that they are mostly saturated, or slightly oversaturated, with respect to SiO_2. The olivine-basalt group, which is the exception, is only slightly undersaturated, and, as has been indicated, these rocks closely resemble in chemical composition a widespread group of Victorian olivine-basalts whose composition borders between saturation and undersaturation. Whereas these Victorian basalts differentiated towards end-products more or less typical of undersaturated magma, the East Kimberley basalts have differentiated towards saturated types, such as the quartz-basalts.

In Table IV. the average composition of these East Kimberley basalts is compared with the average composition of basalts from several other regions. It will be seen that the East Kimberley rocks are intermediate between the typical undersaturated "olivine-basalt magmas" and the typical oversaturated "tholeiitic magmas" (Kennedy, 1933) or "plateau-basalt magmas" (Washington, 1922). The affinities of the East Kimberley suite are with the "tholeiitic magma type."

TABLE IV.

	1.	2.	3.	4.	5.	6.
SiO_2	45	50	52·2	50·5	50	51·3
Al_2O_3	15	15	14·5	14·8	13	13·9
FeO Fe_2O_3	13	11·5	11·2	11·5	13	13·1
MgO	8	8·5	5·0	6·0	5	5·5
CaO	9	8·5	7·3	10·9	10	9·8
Na_2O	2·5	3	2·9	2·9	2·8	2·8
K_2O	0·5	1·2	2·0	0·5	1·2	0·7

1. Olivine-basalt magma type (Hebridean Plateau Magma type). W. Q. Kennedy, *Summ. Prog. Geol. Surv. Gt. Brit.*, 1930, II., 66; *Amer. Journ. Sci.*, Ser. 5, **25**, 1933, 239.
2. Probable parent magma of Victorian Newer Volcanic Series. A. B. Edwards. *Quart. Journ. Geol. Soc. Lond.*, **94**, 1938, 313.
3. Average East Kimberley basalt (7 analyses).
4. Average Tertiary tholeiite from south-western Western Australia. A. B. Edwards, *Journ. Roy. Soc. W.A.*, vol. **XXIV.**, 1937-38, p. 7.
5. Tholeiitic Magma Type (Non-porphyritic Central Magma type), W. Q. Kennedy (as above under 1).
6. Average Deccan basalt (16 analyses), G. W. Tyrrell and K. S. Sandford, *Proc. Roy. Soc. Edin.*, 53, 1933, III., 312.

It seems clear, as Barth (1936) contends, that we have no assurance of the existence of a uniform world-wide primary magma, and that while there are undoubtedly two main types of basaltic lava—an undersaturated one ("olivine-basalt magma type"), characterized by an alkaline, quartz-free residuum; and an oversaturated one ("tholeiitic magma type"), characterized by a quartzo-felspathic residuum—there are also primary magmas of all compositions intermediate between these two extremes. Barth deduces on theoretical grounds that basalts poorer in SiO_2 than a certain composition must differentiate to give an under-silicated residuum, while basalts richer in SiO_2 than a certain composition must differentiate to give a quartzose residuum. The course of differentiation followed by basalts intermediate between these two limiting compositions, e.g. the Footscray type of Victorian Newer Basalt, and the olivine-basalts of the East Kimberley suite, will depend partly on their composition—whether it veers towards undersaturation or oversaturation—and partly on the condition attending early crystallization, e.g., whether it gives rise to early olivine, which is not resorbed, and yet leaves the residual magma undersaturated, as in the Victorian province, or makes the residual magma oversaturated, as appears to have happened in the East Kimberley province.

CONCLUSIONS.

The Cambrian basalts of the East Kimberley district of Western Australia are in the main, fine-grained types, saturated with respect to SiO_2 and poor in olivine. They range from olivine-basalts to quartz-basalts, and have distinct affinities with the tholeiitic—or plateau-basalts, although they appear to be derived from a magma on the border-line between under-saturation and oversaturation. If differentiates more acid than the quartz-basalts described above are found in these regions, they should be andesites.

They appear to form a single basaltic province, but the possibility must be kept in mind that they may comprise flows of two ages, one being Cambrian and the other somewhat younger.

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